

APPLICATION FOR UNITED STATES PATENT

ADAPTIVE LINK DELAY MANAGEMENT IN WIRELESS LINK SYSTEMS

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ADAPTIVE LINK DELAY MANAGEMENT IN WIRELESS LINK SYSTEMS

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BACKGROUND OF THE INVENTION

The present invention relates to wireless networks, and more particularly to systems and methods for improving system timing.

Wireless bridge systems can efficiently and inexpensively interconnect data packet networks in campus areas by utilizing the unlicensed 2.4GHz ISM band and 5GHz
10 UNII bands. It is desirable to use popular wireless local area network (WLAN) standards such those belonging to the IEEE 802.11 family. In particular, the medium access control (MAC) procedures in the IEEE 802.11 standard can be used to coordinate and share the wireless medium between bridge stations. A problem arises in that the IEEE 802.11 MAC protocols assume that all wireless links have radio propagation delays of at
15 most 1 microsecond. However, a point-to-multipoint wireless bridge system may have links that are miles long. Propagation delays on these links can be tens of microseconds, and can vary sharply among links.

The primary access protocol for 802.11 networks employs so-called "CSMA/CA" (Carrier-sense multiple access with collision avoidance) techniques. Contention-free
20 periods are optionally provided within this CSMA/CA scheme. During contention periods, 802.11 stations can transmit if they believe the shared medium is free. The medium may be deemed to be not free based on either physical layer detection of a current transmission or based on a MAC layer detection of a current transmission. The

MAC layer detection depends on monitoring of a duration field in received packets. The duration field may be found in the packet itself, or in a Request to Send (RTS) or Clear to Send message preceding the packet. When a new packet, RTS, or CTS is heard, a timer
5 (the so-called NAV timer) can be set based on this duration field. Until this timer expires, the medium is considered to be busy. After a busy time is completed, each station will continue to defer transmission for a duration defined in part as a multiple of a locally computed random number and a system slot time.

When there is no shared understanding of system timing, there is a much higher
10 probability of collisions due to breakdown of the MAC layer collision avoidance mechanism. Expiration of a prospective transmitter's NAV timer may not be a realistic indication of medium availability from the perspective of the intended receiver. At the conclusion of the busy period, a transmitter that begins a transmission right at the beginning of a slot may potentially collide with other transmitters that are beginning
15 transmission on that slot or some portion of the previous slot due to the varying understanding of the slot boundaries and delayed detection of simultaneous transmissions due to link propagation delays. As link distances increase, packet collision probabilities will also increase unless timing boundaries are well understood at all stations.

Furthermore, physical layer carrier sense mechanisms may not be helpful in a
20 wireless campus network due to the well-known hidden terminal problem. A root bridge of the wireless campus network typically uses an omni-directional antenna while the non-root bridges use directional antennas pointed at the root bridge. Thus the root bridge may hear multiple simultaneous transmissions from non-root bridges that collide because they

do not hear each other. Thus, much larger collision probabilities can be expected when 802.11 techniques are extended to campus-scale wireless networks.

Fig. 1A depicts a simple example indicative of the type of problems that may arise. A wireless network includes a root bridge (RB) and two non-root bridges (NRB1 and NRB2).

- 1) NRB1 starts to transmit a frame, t_1 before the timing boundary of RB (t_0). NRB1 and NRB2 cannot hear each other.
- 2) RB consider the wireless medium “idle” if t_1 is less than the propagation delay between RB and NRB1 (T_1). Then RB starts to send a frame at t_0 .
- 3) NRB2 consider the wireless medium “idle” if t_2 is less than the propagation delay (T_2) between RB and NRB2. Then NRB2 starts to send a frame at $t_0 + t_2$.
- 4) The packet collision duration for the 1st slot of RB is therefore expanded to $t_1 + T_{\text{slot}} + t_2$.
- 5) The maximum packet collision duration for the 1st slot of RB is $T_1 + T_{\text{slot}} + T_2$. Thus average packet collision probability also increases in proportion to $1 + (T_1 + T_2) / (2 * T_{\text{slot}})$.

A more complete quantitative analysis of this effect will be presented later in this document. What is needed are systems and methods for adapting 802.11 techniques to networks with larger propagation delays such as campus point-to-multipoint wireless networks.

SUMMARY OF THE INVENTION

Embodiments of the present invention provide systems and methods for adapting IEEE 802.11 wireless communications for environments involving long propagation
5 delays. Improved system throughput and stability are provided. Propagation delays are measured systematically and used to adjust contention timing boundaries and a common time slot duration. This reduces the probability of collision in the CSMA/CA mode of the IEEE 802.11 standard. One particular application is a point-to-multipoint campus bridge network.

10 A first aspect of the present invention provides a method for operating a point-to-multipoint wireless communication network. The method includes: measuring link delays between a root bridge and a plurality of non-root bridges and using the measured link delays to coordinate transmissions in a CSMA/CA scheme.

A second aspect of the present invention provides a method for operating a node
15 in a point-to-multipoint wireless communication network. The method includes: receiving a measured link delay and a system slot time from another node and using the measured link delay and the system slot time to coordinate transmissions in a CSMA/CA scheme.

A third aspect of the present invention provides apparatus for operating a node in
20 a point-to-multipoint wireless communication network. The apparatus includes a link delay counter that measures delays between a root bridge and a plurality of non-root

bridges and a MAC processor that uses the measured link delays to coordinate transmissions in a CSMA/CA scheme.

5 A fourth aspect of the present invention provides apparatus for operating a node in a point-to-multipoint wireless communication network. The apparatus includes: a physical layer block that receives a measured link delay and a system slot time from another node and a MAC layer processor that uses the measured link delay and the system slot time to coordinate transmissions in a CSMA/CA scheme.

10 Further understanding of the nature and advantages of the inventions herein may be realized by reference to the remaining portions of the specification and the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1A depicts problems with timing of transmissions in a point-to-multipoint wireless network with significant propagation delays.

5 Fig. 1B depicts a point-to-multipoint wireless network according to one embodiment of the present invention.

Fig. 2 depicts elements of a bridge station according to one embodiment of the present invention.

10 Fig. 3 depicts elements of a link delay measurement subsystem according to one embodiment of the present invention.

Fig. 4 is a flowchart describing steps of roundtrip delay measurement and parameter distribution according to one embodiment of the present invention.

Fig. 5 depicts the timing of transmissions from a root bridge to a non-root bridge according to one embodiment of the present invention.

15 Fig. 6 depicts the timing of transmissions from a non-root bridge to a root bridge according to one embodiment of the present invention.

Fig. 7 depicts downlink collision probabilities in an IEEE 802.11a system.

Fig. 8 depicts downlink collision probabilities in an IEEE 802.11b system.

Fig. 9 depicts uplink collision probabilities in an IEEE 802.11a system.

Fig. 10 depicts uplink collision probabilities in an IEEE 802.11b system.

DESCRIPTION OF SPECIFIC EMBODIMENTS

Representative Network Environment

Embodiments of the present invention will be described with reference a
5 representative wireless communication network 100 as depicted in Fig. 1B. Network 100
is a point-to-multipoint wireless network. All communication is either to or from a root
bridge 102. The other nodes are non-root bridges 104 denoted as NRBx. Each non-root
bridge 104 communicates with root bridge 102 via a link Lx which has length dx and a
delay tx.

10 Communication is in accordance with one of the variants of the IEEE 802.11
standard such as, e.g., 802.11a, 802.11b, 802.11g, etc. Generally speaking, the different
flavors of 802.11 vary in their physical layers but are highly similar in their MAC layer
operation. All of the relevant specification documents are incorporated herein in their
entirety for all purposes.

15 Fig. 2 depicts a block diagram of a typical bridge station 200 in network 100
according to one embodiment of the present invention. A physical layer/RF block 202
transmits and receives RF signals via an antenna 204. Physical layer/RF block 202
incorporates circuitry to perform functions including modulation, demodulation,
upconversion, downconversion, conversion between digital and analog, low noise
20 amplification of received signals, and power amplification of signals to be transmitted.
Physical layer/RF block 202 operates in accordance with the relevant flavor of the IEEE

802.11 standard. A MAC layer processor 206 implements MAC layer functionality required by the IEEE 802.11 standard including timing of transmit and receive operations and framing/deframing. A host processor block 208 performs overall control and
5 exchanges data with a local network via an Ethernet connection. Any functionality of bridge station 200 may be accomplished by software that would be stored on a computer-readable storage medium such as, e.g., a flash memory, other type of memory, hard drive, etc. Software for performing such functions may be transferred on a storage medium such as, e.g., a floppy disk, CD-ROM, DVD-ROM, a carrier signal, etc.

10 An overview of 802.11 MAC layer timing coordination will be useful background for the discussion that follows. Two coordination mechanisms are provided by 802.11 systems. One referred to as the distributed coordination function (DCF). This is a CSMA/CA mechanism roughly similar to that used in IEEE 802.3 Ethernet networks. The other is a contention-free access protocol. This mechanism is referred to as the point
15 coordination function (PCF).

The discussion here will focus on the distributed coordination function. Before transmitting, a node will decide whether the wireless medium is busy or idle. The medium may be determined to be busy because the physical layer hears another transmission or because the MAC layer knows that the medium will be busy as will now
20 be explained.

Each node maintains a timer known as the NAV (network allocation vector) timer. The timer tracks reservations of the network by other nodes. For example, each

MAC layer data frame includes a duration field indicating the length of time for which the medium will be reserved to transmit the data frame and its acknowledgement. This duration, incorporating the packet duration, the duration of any expected

5 acknowledgement, and an appropriate interframe spacing (IFS) will be the NAV timer initial value. IFS values are predefined based on priority levels. SIFS is the shortest interframe spacing and provides the highest priority level. PIFS is longer than SIFS and thus indicates a lower priority. PIFS is used by PCF. DIFS is typically used by DCF and is longer than PIFS. There is also an EIFS (extended interframe spacing) period.

10 To alleviate hidden terminal problems, transmission of a data frame may be preceded by an exchange of Request to Send (RTS) and Clear to Send (CTS) frames. This scheme is referred to as multiple access collision avoidance (MACA). These frames will include duration fields indicative of the reservation time for the cycle of transmissions involved in communicating and acknowledging the data frame. The NAV
15 timer value can then be set in response to this duration value even if the data packet is not heard.

The NAV timer counts down from its initialization value to zero. After expiration of the timer and the specified IFS period, there will be a backoff time before a node can transmit. The backoff time is computed to be the product of a locally computed random
20 number and a system slot time. The random number generation is uniformly distributed between 0 and CW, a contention window value. In the event of a packet collision, this same backoff time computation is used to determine the timing of a retransmission

attempt following an EIFS period. If the physical layer detects a busy condition, the backoff timer stops counting down until the medium becomes idle.

The present invention is not to be considered as limited to the above-described
5 environment.

Establishment of System Timing Parameters

Embodiments of the present invention avoid collisions and improve system throughput by adjusting timing parameters such as the NAV timer value and the system slot time. These adjustments are based on a systematic collection of propagation delay
10 measurements in network 100. These delays may be readily measured based on departure and arrival times of RTS and CTS frames, respectively, as measured at root bridge 102. The updated common slot time value is calculated based on the maximum propagation delay, i.e., $aSlotTimeAdj = aSlotTime + t_{max}$, where $aSlotTime$ is a fixed duration, such as 9 microseconds for 802.11a and 20 microseconds for 801.11b, and t_{max}
15 is the longest measured link delay.

Fig. 3 depicts a link delay measurement system 300 to be incorporated into bridge station 200. RTS frames to be sent are accumulated in an RTS buffer 302 while received CTS frames are accumulated in a CTS buffer 304. A link delay counter 306 runs after RTS transmission until receipt of the CTS and is clocked by a clock generator 308.

Root bridge 102 measures delays repeatedly and averages the measured delay on each link. The link delays are distributed to the non-root bridges along with a newly computed system slot time.

5 Fig. 4 is a flowchart describing steps of roundtrip delay measurement and parameter distribution according to one embodiment of the present invention. A step 402 sets a repetition counter to $R=1$. At step 404, a link index is set to $i=1$.

At step 406, the packet address of the next RTS frame to be sent from RTS transmit buffer 302 is set to the non-root bridge for link i . At step 408, link delay counter 10 306 is reset to zero when this RTS frame in RTS transmit buffer 302 is ready to be sent to the physical layer/RF block 202, and then starts to count clock cycles of clock generator 308. The clock frequency of the clock generator, $aClockFreq$ in MHz, should be sufficiently high, for example, 10 MHz, to provide adequate resolution in link delay measurement. The RTS frame is fully sent to the wireless medium after the duration of 15 the RTS frame, $aRTSTime$, plus some physical layer/RF device delays, $aRFTxDelay$. Then the RTS frame arrives at a specified non-root bridge after the propagation delay on the link between the root bridge and the non-root bridge, $aPropagationDelay$. The non-root bridge processes the RTS frame within a specified SIFS time, $aSIFSTime$, and then send a CTS frame to the root bridge in $aSIFSTime$ from the RTS frame receive 20 completion at the receiver physical layer/RF block. The CTS frame arrives at the root bridge after the propagation delay on the wireless medium, $aPropagationDelay$. The MAC processor confirms the CTS frame after the CTS packet duration, $aCTSTime$, plus a physical layer/RF delay, $aRFRxDelay$, plus a MAC processing delay, $aMACPrdDelay$.

A step 410 tests for arrival of the CTS packet. As long as step 412 does not detect a timeout condition, step 410 repeats until the arrival of the CTS frame. When MAC processor 206 identifies the CTS frame from the non-root bridge, at step 414, it stops link delay counter 306, and then read the counter value, aCounterValue. Then, also at step 5 414, MAC processor 206 calculates the roundtrip delay, aRoundTripDelay in microseconds, as follows:

$$\text{aRoundTripDelay} = \text{aCounterValue} / \text{aClockFreq} - \text{aRTSTime} - \text{aCTSTime} - \text{aSIFSTime} - \text{aRFRxDelay} - \text{aMACPrcDelay}.$$

10 The aRFRxDelay and aMACPrcDelay are substantially fixed values in the bridge system, and can be measured in a laboratory environment. The aRFTxDelay value is included in the roundtrip delay value. The link delay, aLinkDelay, is obtained by dividing the aRoundTripDelay by 2.

A step 416 increments the link index i. Step 416 can also be reached after a timeout of link delay counter 306 as would be detected at step 412. A step 418 tests 15 whether i is greater than N, the number of non-root bridges in the system. If not, the next link is measured by returning to step 406. If all of the links have been visited in this repetition of the link measurement algorithm, a step 420 computes an average link delay for each link based on the measurement repetitions. A step 422 then tests whether R, the repetition index, has exceeded a maximum. If it has not, another round of measurements 20 of all the link delays begins by returning to step 404.

If the desired number of repetitions has been completed then final calculations are completed at a step 424. The root bridge updates a common slot time value, aSlotTimeAdj, based on a maximum link delay value, aMaxLinkDelay, selected from the measured average link delay values, i.e., $aSlotTimeAdj = aSlotTime + aMaxLinkDelay$.
The common slot time value and the link delays are distributed to all non-root bridges via MAC layer management frames.

When the root bridge receives an Association Request message from a non-root bridge that wants to join the existing wireless bridge network, the root bridge starts to measure the link delay on the new link after finishing the usual association procedures. Upon the root bridge receiving a Disassociation Request message from a non-root bridge, it deletes the non-root bridge from the non-root bridge list immediately, updates the maximum link delay value and the common slot time value, and then distributes the updated values to all non-root bridges in the newly configured bridge network.

As the root bridge usually needs to send much more traffic to non-root bridges than vice versa, it is preferable to give it priority in accessing the wireless medium. After measuring link delays and updating the common time slot value, the root bridge may employ PIFS rather than SIFS in computing its NAV timer value while the non-root bridges employ DIFS where $aPIFSTime = aSIFSTime + aSlotTimeAdj$ and $aDIFSTime = aSIFSTime + 2 \times aSlotTimeAdj$. With the shorter deferral time, the non-root bridge is more likely to seize control of the wireless medium.

Alternatively, the transmission deferral times for non-root bridges are adjusted based on distance from the root bridge or some other parameter. All else being equal, longer links have lower throughput due to the greater effects of noise and interference.

- 5 One can divide the non-root bridges into groups. For example, the various groups may have aDIFSTime values of $aSIFSTime + 2 \times aSlotTimeAdj$, $aSIFSTime + 3 \times aSlotTimeAdj$, $aSIFSTime + 4 \times aSlotTimeAdj$, etc.

Packet Transmission Using System Timing Parameters

10 Figs. 5-6 illustrate a cycle of packet transmissions in a simplified bridge system that is composed of a root bridge and two non-root bridges, NRB1 and NRB2. The non-root bridges have disparate link paths and link delays to the root bridge. The delay between the root bridge and NRB1 is t_1 while the delay to NRB2 is t_2 . Fig. 5 shows packet transmissions for transmitting data from the root bridge, while Fig. 6 shows packet transmissions for transmitting data from the non-root bridges.

- 15 One set of packet transmissions under the rule of MACA is composed of an RTS packet and a CTS packet followed by a DATA packet and an ACK (Acknowledge) packet. NAV1 (Network Allocation Vector 1) and NAV2 (Network Allocation Vector 2) are contention-free durations, which are set by the root bridge to protect DATA packets from collisions on the wireless medium. The root bridge calculates the NAV value of
20 each set of MACA packets, which includes the durations of RTS, CTS, DATA, and ACK packets, SIFS, and link delays. Then the root bridge distributes the NAV values to all non-root bridges via the RTS and CTS packets.

In Fig. 5, for the first set of MACA packet transmissions, the duration of NAV1, aNAV1Time, is calculated at the root bridge as follows:

$$\text{aNAV1Time} = 4 \times t1 + 3 \times \text{aSIFSTime} + \text{aCTSTime} + \text{aDATA1Time} +$$

- 5 aACKTime, where aSIFSTime, aCTSTime, aDATA1Time, and aACKTime are the durations of SIFS, CTS, DATA1, and ACK, respectively. If each non-root bridge subtracts its own link delay from the received NAV value, the wireless bridge system can have a common timing reference for medium contention among all bridge stations. Accordingly, NRB1 adjusts its packet duration value to aNAV1Time – t1, and NRB2
- 10 adjusts its NAV value to aNAV1Time – t2. This guarantees fairness in the starting point of medium contention for the next packet transmission for all bridge stations.

Likewise, for the second set of MACA packet transmissions, the duration of NAV2, aNAV2Time, is calculated at the root bridge as follows:

$$\text{aNAV2Time} = 4 \times t2 + 3 \times \text{aSIFSTime} + \text{aCTSTime} + \text{aDATA2Time} +$$

- 15 aACKTime, where aDATA2Time is the duration of DATA2. The timing alignment procedures are the same as in the first set of MACA packets.

If RTS/CTS packets are not used prior to sending a DATA1 packet with the duration of aDATA1Time, the duration value in the DATA1 packet, aDuration, can be calculated at the root bridge as follows:

- 20 $\text{aNAV1Time} = 2 \times t1 + \text{aSIFSTime} + \text{aDATA1Time} + \text{aACKTime}$. NRB1 then adjusts its packet duration value to aNAV1Time – t1, and NRB2 adjusts its NAV value to

aNAV1Time – t2, resulting in guaranteed fairness in the starting point of medium contention for the next packet transmission.

Referring now to the first MACA packet transmissions in Fig. 6, NRB1 sends an
5 RTS packet with its NAV value, aNAV1TimeRTS as calculated by:

$$\text{aNAV1TimeRTS} = 3 \times \text{aSIFSTime} + \text{aCTSTime} + \text{aDATA1Time} + \text{aACKTime}.$$

The root bridge calculates its NAV1 value, aNAV1Time, from the NAV value in the received RTS packet, as below:

aNAV1Time = aNAV1TimeRTS – aCTSTime – aSIFSTime + 2 x t1 + t2, where
10 t2 is the largest propagation delay in the bridge system.

As in Fig. 5, each non-root bridge adjusts its received NAV value in the CTS packet by its own link delay. Thus, NRB1 adjusts its NAV value to aNAV1Time – t1, and the NRB2 adjusts its NAV value to aNAV1Time – t2.

Referring now to the second set of MACA packet transmissions in Fig. 6, the
15 NRB2 sends an RTS packet with its NAV value, aNAV2TimeRTS as below:

$$\text{aNAV2TimeRTS} = 3 \times \text{aSIFSTime} + \text{aCTSTime} + \text{aDATA2Time} + \text{aACKTime}.$$

Then the root bridge calculates the NAV2 value, aNAV2Time, from the NAV value in the received RTS packet, as follows:

aNAV2Time = aNAV2TimeRTS – aCTSTime – aSIFSTime + 2 x t2 + t2. This
20 procedure can be generalized to any number of non-root bridges by replacing t2 in the above equation with a maximum link delay value, t_{max}, in the bridge system.

In each case, after expiration of the NAV timer, or after another type of medium busy detection, the backoff time is a locally computed random number multiplied by the system slot time which has been computed as previously described.

5 **Theoretical Background**

An analysis of collision probabilities in an 802.11-based bridge system that does not employ the modifications provided by embodiments of the present invention will now be presented.

10 A point-to-multipoint system with directional antennas at non-root-bridges is a kind of “ALOHA” system, in which each non-root bridge cannot hear the other non-root bridges while the root bridge can hear all non-root bridges. ALOHA systems are described in detail in N. Abramson, “The Aloha System – Another Alternative for Computer Communications,” 1970 Fall Joint Computer Conference, AFIPS Conference Proceedings, AFIPS Press, Montvale, NJ, vol. 37, pp. 281-285 (1970), the contents of
15 which are herein incorporated by reference in their entirety. In this situation, it is well known that a non-slotted (packet transmissions are not based on a shared timing reference) ALOHA system with evenly distributed packet transmit probability on each time slot at each station has two times packet collision probability and a half throughput of the corresponding slotted ALOHA system. Similarly, in a point-to-multipoint bridge
20 system where all non-root bridges are equidistant from the root bridge in CSMA/CA mode, if all bridge stations have an initial common contention window value (aCW_{\min}),

the packet collision probability at the 1st attempt on a time slot for the downlinks is given as follows:

Pr (1st collision) = $1 - [1 - 1 / (aCW_{min} + 1)]^{(N-1)}$, if time slot boundaries of bridge
5 stations are well aligned;

Pr (1st collision) = $1 - [1 - (1 + T_d/T_{slot}) / (aCW_{min} + 1)]^{(N-1)}$, if time slot boundaries
of bridge stations are randomly distributed,

where aCW_{min} is a minimum contention window, N is the number of bridge
stations in the system, T_d is the common link propagation delay, and T_{slot} is an updated
10 slot time, that is, $T_{slot} = aSlotTime + T_d$, where $aSlotTime$ is a slot time value specified in
the 802.11 standard, such as 9 microseconds for 802.11a and 20 microseconds for
802.11b.

As shown in the above equations, the packet collision probability at the 1st attempt
increases as the number of bridge stations and the propagation delays increase. As
15 propagation delays on the links increase, packet collision probability in an 802.11a
system increases more rapidly than in an 802.11b system. This is due to shorter slot time
values and smaller aCW_{min} values. Figs. 7-8 illustrate collision probabilities according to
the above equations. Fig. 7 depicts collision probability on the first attempt on
downlinks. Fig. 7 assumes the use of 802.11a and $T_d = 20$ microseconds, corresponding
20 to a link distance of about 4 miles. Fig. 2 depicts collision probability on the first attempt
on 802.11b downlinks, based on similar assumptions.

As shown in Fig. 7, a point-to-multipoint bridge system composed of multiple bridge stations (e.g., N=6) with misaligned time slot boundaries shows high collision probability at the first attempt (e.g., 0.43 for N=6, T_d = 20 microseconds). Likewise, as shown in Fig. 8, the packet collision probability in an 802.11b point-to-multipoint bridge system increases as the number of non-root bridge stations increases and also as the link length increases, while the overall collision probabilities are lower than those of corresponding 802.11a point-to-multipoint bridge systems. This is due to a larger slot time (20 microseconds) and aCW_{min} value (31) than those of 802.11a systems (9 microseconds and 16, respectively).

Although the exponential backoff algorithm of the 802.11 MAC protocol decreases the collision probabilities at the second and following packet transmit attempts, the first packet collision probability affects the overall trend in collision probability and packet transmit delay. Thus the packet collision probability at the first attempt can be a good measure for comparing the performances of 802.11 bridge systems with well aligned and badly aligned time slot boundaries.

The packet collision probability among the non-root bridge stations, which are hidden to each other, can also be calculated approximately for the uplinks of a point-to-multipoint system in CSMA/CA mode employing RTS/CTS as follows:

$$\text{Pr (1}^{\text{st}} \text{ collision)} = 1 - [1 - 1 / (\text{aCW}_{\text{min}} + 1)]^{(M-1)*(1+C)}, \text{ if time slot boundaries of bridge stations are well-aligned;}$$

Pr (1st collision) = $1 - [1 - (1 + T_d/T_{slot}) / (aCW_{min} + 1)]^{(M-1)*(1+C)}$, if time slot boundaries of bridge stations are randomly distributed,

5 where M is the number of non-root bridge stations in the system, $C = T_c / T_{slot}$, T_c is the duration of one RTS plus and one SIFS, that is, $T_c = aRTSTime + aSIFSTime$, where

aRTSTime is the packet duration of RTS and aSIFSTime is the SIFS duration specified in the 802.11 standard, such as 16 microseconds and 10 microseconds for 802.11a and 802.11b, respectively. The aRTSTime depends on physical layer
10 transmission rates; e.g, it may be 47, 33, and 27 microseconds for 6, 12, and 24 Mbps, respectively, in an 802.11a system, and 256 and 176 microseconds for 1 and 2 Mbps, respectively, in an 802.11b system. The other parameters are the same as defined earlier.

Figs. 9-10 illustrate the uplink collision probabilities. Fig. 9 gives the collision probability at the first attempt employing RTS/CTS on uplinks. Fig. 9 assumes the use of
15 802.11a, an RTS/CTS rate of 24 Mbps, and a $T_d = 20$ microseconds, corresponding to a link distance of about 4 miles. Fig. 10 makes the same assumptions as Fig. 9 but for 802.11b. As can be seen in Figs. 9-10, the collision probability of an RTS packet on the first attempt is higher on the uplink than on the downlink.

Without the modifications provided by embodiments of the present invention, it
20 will be seen that throughput will be severely impacted by collisions in 802.11 point to multipoint wireless bridge systems. Aligning contention timing boundaries and modifying the system slot time based on measured link delays is very effective in reducing packet collision probability and thus improving overall system throughput.

It is understood that the examples and embodiments that are described herein are for illustrative purposes only and that various modifications and changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and
5 purview of this application and scope of the appended claims and their full scope of equivalents. For example, in alternative embodiments, delay measurements may be computed and processed by one or more of the non-root bridges. Also, embodiments of the present invention could be applied to any suitable wireless network employing an access point and stations where propagation delays cause the MAC layer protocol to
10 break down.